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6. AUTHOR(S)
R. E. Camley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Colorado at Colorado Springs
PO Box 7150
Colorado Springs, CO 80933-7150

8. PERFORMING ORGANIZATION REPORT NUMBER
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13. ABSTRACT (Maximum 200 words)

This report describes research done under this project on the basic physics of magnetic multilayers
The work done covered both fundamental and applied problems.
Among the problems studied were:

1) Surface phase transitions and spin wave modes in Fe/Cr superlattice
   This project was a collaboration with Argonne National Labs and the theoretical calculations explained the experimental results showing an extra peak in the magnetic susceptibility was due to a surface phase transition.
2) Electromagnetic response of magnetic materials
   Here we studied the interaction of high frequency EM waves (10 - 100 GHz) with structured magnetic materials.
   We also studied higher frequency modes (100-1000 GHz) in antiferromagnets
3) The influence of eddy currents on bulk and surface spin wave modes in metallic ferromagnets
4) Exchange Biasing
   We showed that the spin wave frequencies of a thin Fe film could be increased substantially by coupling a Fe film to SmCo. A mul tilayer of Fe/SmCo could be used as an active element in a notch filter at high frequencies.

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Statement of Major Problems Studied

1) Surface Phase Transitions

An important problem in the field of magnetic multilayers is the nature of magnetic phase transitions. In contrast to many bulk materials, these phase transitions can nucleate at the surface and occur at quite modest applied magnetic fields. They can also cause substantial changes in the materials properties such as susceptibility or resistivity. We examined magnetic field induced spin reorientation transitions induced in magnetic superlattices which incorporate exchange coupled ultrathin ferromagnetic films. These structures, including, for example, Fe/Cr and Co/Cu multilayers, are fundamental to the giant magnetoresistance effect and so a proper understanding of the equilibrium states as well as the magnetic excitations is essential.

2) Electromagnetic Response of Magnetic Materials

Magnetic materials such as YIG have been used for many years for signal processing at lower frequencies. There is now a need to work at higher frequencies and we have investigated new magnetic materials and structures to determine their suitability for this task.

A long-standing practical problem is whether one can use metallic magnetic materials as signal processing elements at high frequencies. Normally this can not be done since the high reflectivity prevents an electromagnetic wave from penetrating into the magnetic material. This is also a fundamental problem since measurements (infra-red and microwave reflectivity) which can determine the basic properties of these magnetic materials are also prevented. We proposed and investigated theoretically a solution - structured magnetic films - which allows one to use the magnetic properties of the material but which eliminate the undesirable metallic behavior.

We also investigated the electromagnetic properties of antiferromagnets that can have excitation frequencies which are very high -- on the order of 100 to 1000 GHz.

3) Eddy Currents

A central issue in the theory of the magnetic response of magnetic films and multilayers is the lifetime or the mean free path of spin wave excitations. Most discussions in the literature characterize this in a simple phenomenological fashion, utilizing the Bloch equations modified by suitable damping terms. This theoretical structure fails to recognize one important aspect of the magnetic thin films and multilayers studied currently: most usually the films of interest are metallic in nature (Fe, for example). There are damping mechanisms specific to metals, and which are not present in insulating materials. We have made a careful study of this mechanism and its influence on spin propagation in films. In addition to its fundamental aspects, this is an important area since thin Fe films have been proposed as the active element in a notch filter designed to work in the 10-30 GHz range.

4) Exchange Biasing

A fundamental issue in the field of magnetism is how two different magnetic materials can influence each other due to some kind of magnetic coupling at the interface between the two materials. In the simplest cases, we can imagine one material exerting an effective field on the second which can alter the magnetic configuration of the entire structure. This coupling then can strongly influence the static properties of the multilayer.

A more subtle situation, where the interfilm coupling influences the dynamic modes of the multilayer has been less studied until recently. It has been proposed that thin iron films can be the active element in signal processing in the 20 GHz region. We studied how this frequency range could be extended to the 20-80 GHz range by coupling the iron film to a Sm-Co film. A second major area of research involved increasing the spin wave frequencies in ferromagnets by coupling them to antiferromagnets. Experimentally it has been observed that the frequency of surface excitations in thin Co films could be doubled (from 20 GHz to 40 GHz) due to the presence of a very thin antiferromagnetic layer of CoO. This is quite exciting since such an increase is equivalent to applying an external field of about 8 kG without actually having to produce an external magnetic field.

In addition to the work discussed above, we began calculations aimed at understanding the temperature dependence of the interfilm exchange between ferromagnetic films separated by a nonmagnetic spacer layer. (Again we note that this is the standard magnetic multilayer configuration for many applications including giant magnetoresistance.) The interfilm exchange is a fundamental quantity that controls magnetization of the entire structure as well as the splitting in frequency between optical and acoustical spin wave modes in multilayer structures.

Summary of Most Important Results

1) Surface Phase Transitions

This project featured a collaboration with researchers at Argonne National Laboratory which has resulted in the discovery of the surface spin flop transition, a phenomenon predicted by the principal investigator in 1968. The new Fe/Cr(211) superlattices fabricated at Argonne proved to be an ideal system in which to observe this transition. We have also developed the theory of the collective spin wave excitations in such structures, and discussed their properties in a paper published in Physical Review B. Good agreement was found between the theoretical results and the experimental ones found by the researchers at Argonne. These modes are very different in character than envisioned in the early papers, by virtue of the very strong interfilm dipolar couplings present in the superlattice structures.

We also studied theoretically the low-frequency dynamic response of magnetic superlattices. Particular attention is given to the Fe/Cr(211) structure, which has been demonstrated to have a surface or bulk spin-flop phase, depending on the number of magnetic layers. We use a new calculational method for finding the equilibrium structure which eliminates some of the difficulties found in earlier schemes. We proceed by integrating the equations of motion of the coupled magnetic films in time, for an extended period. We include Landau-Lifshitz damping in the equations of motion, and drive the structure with an appropriate low-frequency field. The externally applied (nominal) dc magnetic field is increased slowly. We can follow the structure through the sequence of magnetic field-induced phase transitions. By this means, we obtain the magnetic phase diagram, χ_1 and χ_2 along with hysteresis curves in a single calculation. We also provide data on the magnetic-field dependence of the low-field susceptibility, which is in good accord with theory.

2) Electromagnetic Response of Magnetic Systems

In our work we showed that a magnetic film could be structured (by cutting grooves in it) so that the electron motion is inhibited, and thus the high metallic reflectivity is eliminated. The geometry of the grooves can be chosen so that the magnetic response, desired for signal processing or for basic measurements, remains even while the high reflectivity associated with electron motion is restricted. This is done by making the dynamic electric field transverse to the grooves. We were able to show that this method should work for both metallic ferromagnets (with frequencies in the 20-40 GHz range) and for metallic antiferromagnets (frequencies in the 100-1000 GHz range). Our calculations show that significant nonreciprocal reflection may be obtained for these structured metallic magnets, opening the way for possible device applications.

Much of our work focused on the propagation of electromagnetic waves in insulating antiferromagnets. In general insulators are generally the material of choice for signal processing since the incident electromagnetic wave is not significantly attenuated inside the material. Antiferromagnets can have excitation frequencies that are very high -- on the order of 100 to 1000 GHz. We have been working with an experimental group at the University of Essex to study infrared reflectivity from insulating FeF_2. The results have been quite exciting! We have found that a reversal of propagation direction can lead to a reflectivity change from 80% to nearly zero! This seems quite promising for future device applications. Our work made direct contact between two different kinds of experimental measurements - infrared reflectivity and attenuated total reflection (ATR) reflectivity. The ATR measurements were of particular interest because one could see direct evidence of nonreciprocal surface spin waves in antiferromagnets.

3) Eddy Currents

When a spin wave is excited, the precessing magnetization necessarily induces an electric field, by virtue of Faraday's Law. In the conducting medium , Ohmic dissipation then results from the currents stimulated by the electric field. We have worked out the theory of this effect, to find most interesting results. The damping can be quite strong, but in fact depends on the wave vector of the spin wave mode. At zero wave vector, corresponding to the uniform spin wave excited in a resonance experiment, this eddy current damping is absent. For wavelengths comparable to the microwave skin depth, however, its influence can become severe.

We considered a structure where propagation was perpendicular to the magnetization, which is parallel to the surface, and wavelengths sufficiently long that the influence of exchange may be ignored. Precession of the magnetization induces eddy currents that damp the spin waves, and also renormalize the dispersion relation of the Damon-Eshbach mode encountered in this geometry. We provided analytic formulas that describe these effects, in various limits. We used a Green's function method to study the influence of conductivity on the whole spectrum of spin fluctuations and in various wavelength regimes. One of the most important results is that when the thickness of the film is less than the skin depth caused by the eddy current damping, it is the thickness of the film (rather than the skin depth) which controls the dispersion relation of the spin wave.

4) Exchange Biasing

We have investigated the effect of coupling a soft magnetic material (Fe) to a magnetically hard material (SmCo) for use in high frequency applications (20-100 GHz). This work was motivated, in part, by experimental work at Argonne National Labs. The basic idea of this is as follows. Since the Sm-Co film has a high anisotropy, the spin motion in Sm-Co is "stiffer." The spins in Sm-Co are exchange-coupled to the Fe spins at the interface making the Fe spins "stiffer" and resulting in a higher frequency. Our theoretical calculations showed how the dynamic susceptibility of the Fe/SmCo structure depended on the thickness of the constituents and on their magnetic properties. The basic results were that the Voigt permeability could be shifted to substantially higher frequencies by layering Fe with SmCo. This means that the effective magnetic response is simply shifted to these higher frequencies. We then showed how these coupled materials could be used in high frequency filters. Our theoretical calculations show it is possible to boost the frequency for a notch filter from 20 GHz to about 80 GHz. The same structure can be a band-pass filter at even higher frequencies.

We investigated a second exchange biasing system based on the interaction of ferromagnets with antiferromagnets. This is the typical material combination that is used in magnetic sensors. Experimentally it had been observed that the frequency of surface excitations in thin Co films could be doubled (from 20 GHz to 40 GHz) due to the presence of a very thin antiferromagnetic layer of CoO. In collaboration with Cambridge University we developed a theoretical model that showed how the coupling of the spins in Co to those in the antiferromagnet CoO could produce substantial shifts in the basic ferromagnetic spin wave in Co. The key point is that spins in CoO experience significantly larger anisotropy fields than those in Co. As a result of the interfacial coupling, the spins in the Co film have their frequencies shifter upward. We explained the temperature dependence of this effect using this model and obtained excellent agreement with the experimental results found at Cambridge.

In addition to the work discussed above, we completed calculations aimed at understanding the temperature dependence of the interfilm exchange between ferromagnetic films separated by a nonmagnetic spacer layer. (Again we note that this is the standard magnetic multilayer configuration for many applications including giant magnetoresistance.) The interfilm exchange is a fundamental quantity that controls magnetization of the entire structure as well as the splitting in frequency between optical and acoustical spin wave modes in multilayer structures. By considering spin wave interactions, we are able to show that the interfilm exchange coupling should have a temperature dependence of the form $T^{3/2}$.

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(We note that the primary work on the following papers was done under other ARO grant sponsorship, but that some support for this work was also provided by this grant.

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R. L. Stamps and R. E. Camley
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Participating Scientific Personnel

At University of Colorado, Colorado Springs

R. E. Camley	Principal Investigator
R. L. Stamps	Post Doctoral Visitor
B. V. McGrath	MS earned during project
R. J. Astalos	MS earned during project
D. B. Fulghum	MS earned during project

At University of California, Irvine

D. L. Mills	Principal Investigator
R. W. Wang	Ph.D. earned Sept 94
N. S. Almeida	Visiting researcher
S. Rakhmanova	Post Doctoral researcher

Inventions Reported

none